PROPELLER CAVITATION IN SOLUTIONS OF POLYETHYLENE OXIDE

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THESIS

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OF POLYETHYLENE OXIDE

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ABSTRACT

The inception and formation rates of bubble cavitation on a 14.8-cm diameter, two-bladed propeller were measured in homogeneous aqueous solutions of polyethylene oxide, WSR-301, at concentrations ranging from 0 to 100 wppm (weight parts per million). Rotational speeds ranged from 1300 to 2000 rpm. At concentrations of 25 wppm and greater, inception was delayed by approximately 150 rpm, and at 2000 rpm the number of bubble collapses measured over a 10-second period was reduced by at least 40 percent. If these results can be extended to full size propellers, ships can increase their propeller rotation rate while producing the same amount of cavitation noise. Measurements of the radiated noise spectra of bubble collapses showed that the higher frequency components are somewhat attenuated in polyethylene-oxide solutions.

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I. INTRODUCTION

A. GENERAL

The study of drag reduction dates from 1948 when Toms [1] found a correlation between increased flow rate and concentration for the turbulent flow of polymer solutions in pipes. The "Tom's Phenomenon" was of little interest until it was realized that costs of pumping fluids could be significantly reduced by adding small amounts of long-chain polymers.

B. WATERBORNE VEHICLES

Naval engineers soon became interested in the use of polymers to reduce drag on waterborne vehicles. The first studies were of flat plates moving through a fluid, and then other geometric shapes were tested. Kowalski [2] observed significant reduction of drag on both flat plates and three-dimensional models which were towed in tanks containing dilute solutions of polyethylene oxide. These fluids were referred to as non-newtonian, but standard viscometry tests showed that their behavior was essentially newtonian. It was estimated that to reduce the drag on a 450-ft merchantman at a speed of 18 kt would require 13,000 lb/hr of polymer. The impracticality of such an operation was pointed out. Gollan, Tulin, and Rudy [3] tested ejection systems with a froude-scaled model (11.4-ft length, 1.4-ft girth) and found that over 18% of the total drag, or more than 55% of the frictional drag, could be eliminated when the polymer (at a concentration of 1,000 to 1,300 weight parts per million) was ejected at a rate about ten times the sublayer flow rate.

C. CAVITATION

1. Definitions

Cavitation is defined [7] as "the formation of bubbles, voids, or cavities along side or behind a body moving in a liquid when or where, by reason of the shape of the body, its velocity through the liquid, and the hydrostatic pressure around it, the liquid pressure at the body is reduced nearly to absolute zero, or approximately to the vapor pressure of the liquid". The three basic types of cavitation are bubble, sheet, and super cavitation. Bubble cavitation, which commonly occurs at the tip of a rotating propeller, is characterized by the formation and collapse of a single bubble. A bubble may undergo several cycles of formation, collapse and reformation depending upon environmental factors. At each collapse the bubble generates a broad-band noise burst. Sheet cavitation, which commonly occurs across a section of a hydrofoil face, is characterized by the separation of the liquid from the face of the hydrofoil. The liquid preserves its continuity but leaves a large cavity between itself and the face of the hydrofoil. If pressure forces are such that the liquid rejoins the face of the hydrofoil then this is described as sheet cavitation. If the cavity extends beyond the face of the hydrofoil, then the cavitation is described as supercavitation.

2. Effect of Polymers on Cavitation

Hoyt [4] investigated cavitation on a 7.62-cm diameter test body with a tapered nose shape. The body was located in a free-jet water tunnel with a 27.9-cm diameter jet and a nominal jet velocity of 7.65 m/sec. The fluids used were pure water and

water mixed with 50-wppm polyethylene oxide. Not only were there visual differences in the cavitation stream, (the stream being shorter in length in the polymer solution) but the wall-pressure fluctuations were much less in the polymer solution, indicating a more stable flow pattern.

Ellis [5] found that for a ¼-in. hemispherically-nosed cylinder cavitation was initiated at higher flow rates in solutions of 50-wppm polyethylene oxide than in water. Oscilloscope pictures of the radiated noise showed a rise in noise level to a constant amplitude as cavitation formed. In the polymer solution, the initial rise was similar to that in water but after approximately ½ sec. the amplitude decreased to approximately 70% of the value in water.

Sendek [6] studied the noise radiated from free-falling spheres in water and in a 100-wppm polyethylene-oxide solution. It was found that for a given sphere there was a marked decrease in the noise radiated in the polymer solution. The noise described as "blurps" or "bursts" was assumed to originate from the collapse of cavitation bubbles in the wake. These "bursts" were less in number for a given sphere in the polymer solution.

From the above observations it appears that the addition of polymers to water flowing over a body inhibits the formation of cavitation.

3. Cavitation on Propellers

The studies of cavitation on propellers in water are too numberous to mention. A search of the literature for work done on cavitation on propellers in polymer solutions failed to turn up any papers.

II. NATURE OF THE PROBLEM

The problem chosen was to determine the effects of dilute solutions of polyethylene oxide on the cavitation behavior of a propeller. Measurements were to be made on the threshold and rate of formation of the cavitation as a function of propeller rotation rate and polymer concentration. The spectrum of the radiated noise was to be studied to determine if the polymer influences the character of the radiated sound.

III. APPARATUS

A. TANK

The water tunnel (Figure 1) used was an annular steel tank with an inner diameter of 125 cm, an outer diameter of 314.5 cm, and a depth of 45.5 cm. It is open at the top and has a 16 by 26-in. plexiglas viewing window (Figure 2) mounted in the outer wall. The inside surface of the plexiglas is concave to conform with the contour of the tank. The tank was acoustically isolated from the ground vibrations by isomo rubber pads. It was also electrically grounded.

B. PLYWOOD COVER

A verethane-coated 2.0-cm-thick plywood cover was installed in the tank for a mean radial distance of 64 cm upstream and 208 cm downstream from the propeller (Figure 3). The top of the cover was mounted 39 cm from the bottom of the tank which placed it 3 cm under the surface of the water in a "no flow" condition. A 3.0-cm diameter hole was cut into the cover to allow the 2.2-cm diameter motor shaft to pass through. With the cover and restrictor installed, the flow pattern was such that no bubbles were formed in the wake nor was there any turbulence formed around the motor shaft at the surface of the water.

C. MOTOR AND MOUNT

The motor (Model Number 683S49) and weedless propeller (Model Number 658P04) are component parts of a complete 12-VDC electric troll motor (Model Number 5918)(Figure 4) manufactured by the

Shakespeare Company of Kalamazoo, Michigan. The motor was mounted on a steel-beam support (Figure 5) which weighed approximately 250 lb. The motor casing is 22 cm in length and has a diameter of 6.4 cm. The diameter of the propeller is 14.8 cm. It was assumed that the casing was small enough to consider the propeller to be in the free-field condition. The propeller axis was located 20 cm from the bottom of the tank on the center line of the annulus.

D. FLOW RESTRICTOR

A flow restrictor (Figure 6) was installed at an arc distance of 216 cm downstream from the propeller. It consisted of 10 hollow, free-flooding, stainless-steel pipes of 3.8-cm outer diameter, and 0.25-cm wall thickness, mounted with a gap of 0.5 cm between adjacent elements. This restrictor was needed so that the propeller would work under a heavy load at high speeds; these conditions are required to produce appreciable cavitation. It was observed that at the flow rates used no significant flow noise or undesired turbulence was created.

E. MOTOR CONTROL EQUIPMENT

The motor was driven by a 0-50-VDC power supply rated at 30 A. It was manufactured by Electro-Mechanical Products of Garden City, Michigan (MFR's No. 49007-R). When the motor was operating at its full capacity of 12V, the current was 24 A. The motor voltage was monitored by a Hewlett Packard Model 410B vacuum-tube voltmeter. Motor current was monitored by a Westinghouse Type PX5 direct-current ammeter having a range of 0-25 A. The rotation rate of the propeller was determined by using a General Radio Type 1531-AB Strobotac to "freeze" its motion.

F. RECEIVING AND ANALYZING EQUIPMENT (FIGURE 7)

1. Hydrophone

An Atlantic Research Corporation Piezoelectric Hydrophone (Model LC-32), having a flat free-field voltage response over the range 1-7 kHz was mounted in a vertical position with its "center of acoustic field" on the same horizontal plane as the propeller axis at a distance of 60-cm downstream from the propeller. The hydrophone was isolated from the mount tube, and the mount tube was isolated from the plywood cover by isomo rubber pads.

2. Amplifiers

Three amplifiers connected in series were used to amplify the signal by 80 dB.

a. Atlantic Research LG-1344

This 40-dB gain high-input impedance amplifier (1000 Mohm) was used to match the output impedance of the hydrophone. (This amplifier requires 28 VDC $\pm$ 15% as its power supply.) The output from a 45-V battery was adjusted to 28 V by means of a potentiometer and read on a Westinghouse Type PX-4 DC voltmeter.) The frequency response of this amplifier is rated at $\pm$ 1 dB from 20 Hz to 100 kHz.

b. Burr Brown Model 110

This variable-gain AC preamplifier was used for the second state. Being battery powered, it would minimize undesired 60 Hz signal. The frequency response of this amplifier is rated at $\pm$ 0.5 dB from 10 Hz to 250 kHz.

c. Hewelett Packard 467A Power Amplifier

For the final stage of amplification, this line-powered unit provided a usable signal with minimum distortion and extraneous noise. This amplifier is rated at less than 0.3% distortion from 0-10 kHz and less than 1.0% from 10-100 kHz.

These three amplifiers were adjusted to give an overall amplification factor of 80 dB. The signal-to-noise ratio was established by comparing the signal with the motor running at minimum speed with the signal obtained with the motor turned off. The signal-to-noise ratio was 20:1.

3. General Radio Sound and Vibration Analyzer (GR 1564-A)

This analyzer was used in the cavitation-bubble counting portion of the experiment. The filter was set at a center frequency of 1500 Hz with a 1/10-octave bandpass. The filter characteristics at this setting are an attenuation of at least 40 dB at one half and twice the selected center frequency. This center frequency was chosen because spectral analysis showed that there was little motor or other extraneous noise in this region of the spectrum.

4. Tektronix Type 565 Dual-Beam Oscilloscope

This oscilloscope, with a Type 3A72 dual-trace amplifier plug-in module, was used for several purposes. First, it was used to measure the signal-to-noise ratio. Second, it was used, in conjunction with a General Radio Model 1320 Oscillator set at 1500 Hz, to calibrate the amplification factor of the three amplifiers. Third, it was used to monitor the amplified, filtered hydrophone output before and after it was rectified and demodulated.

The unfiltered cavitation noise appeared on the oscilloscope superimposed upon the motor noise. The cavitation noise was characterized by a sharp leading edge followed by a rise to a peak which was followed by a steep decrease. The height of the peak was variable from barely discernable to approximately twice the amplitude of the background noise. The length of the pulse was on the order of 0.5 msec. Pulses sometimes appeared to overlap.

5. Rectifier and Demodulator

After passing through the 1/10-octave filter, the cavitation noise appeared on the oscilloscope as sinusoidal pulses having, on the average, eight cycles with an amplitude which decayed exponentially.

Since a laboratory counter would see each cycle of the signal, the signal was passed through a rectifier/demodulator (Figure 8). The signal entered a 2:1 center-tap transformer, was fully rectified by a pair of 1N96 silicon diodes, then demodulated in a parallel RC network. (The capacitor value was 0.015 microfarads, and the resistor value was 10.0 megohms.) The middle and lower pair of traces on Figure 9 are two examples of the rectifier/demodulator characteristics. The lower trace of each pair is that from the GR 1564-A, and the upper trace is for the same pulses after they have passed through the rectifier/demodulator.

6. Hewlett Packard 521C Electronic Counter

The counter was set on a 10-second gate to determine the rate at which bubble pulses were received. The number of pulses received in a 10-second period in the water solution (Nw) is to

be compared with the number of pulses received in the various concentrations of the polymer (N_p) for the same propeller rotation rate.

7. Kay Missile Data Reduction Spectograph (675B)

The Kay Missilyzer served a twofold purpose. First, it was used in the spectrum analysis to determine the frequency range in which the cavitation noise dominated other noise sources. Figure 10 shows the amplitude of the unfiltered signal as a function of frequency and time. The continuous narrow-band signals are from the motor and other background sources; the short broad-band pulses are cavitation bursts.

Second, the frequency spectra of the bursts were obtained to determine the characteristics of the cavitation noise. Figure 11 is an example of the frequency spectrum of a single cavitation bubble in water. (The amplitude is logarithmic.)

IV. EXPERIMENTAL PROCEDURE

A. POLYMER MIXING AND DEGRADATION

Polyethylene Oxide (POLYOX) WSR-301 (manufactured by Union Carbide) was the only polymer used in the experiment.

POLYOX is easy to mix in water if the proper precautions are followed. If POLYOX powder were mixed directly into water, it would form large aggregates which take a long time to dissolve. To prevent this, the powder is first mixed with DOW POLYGLYCOL P400 in which it is insoluble. The POLYGLYCOL does not affect the drag reduction properties of the solution, but it holds the polymer particles in suspension, making mixing a simple task.

The tank was first filled with water until the propeller was completely immersed. Then the motor was turned on, and propeller speed was set at about 1000 rpm. The water was turned on again and the slurry of POLYOX and POLYGLYCOL was slowly poured from a beaker into the stream of entering water. When the water level in the tank reached a height which was just below the level of the plywood cover, the water was turned off and the mixture was allowed to circulate for approximately ½ hr. The walls of the tank were visually checked for any undissolved POLYOX and if clear the motor was stopped and the tank was filled to its reference level with water. The motor was again run for another ½ hr to ensure a homogeneous mixture.

A complete set of data was taken from one master solution. This was accomplished by first mixing a solution of 100 wppm.

After making the runs at 100 wppm the tank was drained to one-half reference level and refilled with water to obtain a concentration of 50 wppm. The process was repeated to obtain concentrations of 25 and 10 wppm.

A check on the degradation rate of a solution was made [8]. The motor was run continually at about 1000 rpm for periods up to five hours. It was found that at the end of five hours the solution had the characteristics of a fresh solution whose concentration was 80% of the original concentration.

B. DATA ACQUISITION

After allowing sufficient time for the propeller to stabilize at a fixed rotation rate, the cavitation bursts were counted for 10 intervals of 10 seconds each. After each 10-second interval the number of counts on the counter was recorded. This procedure was carried out for each concentration of polymer used (0, 10, 25, 50, and 100 wppm) at propeller rotation rates from 1550 to 2000 rpm in 50-rpm increments. Only one flow-restrictor setting was used.

A cavitation bubble burst spectrum was obtained for each concentration of polymer used, at a propeller rotation rate of 2000 rpm. The frequency range studied was from 150 Hz to 15 kHz, and the amplitude was displayed logarithmically.

V. EXPERIMENTAL RESULTS

A. CAVITATION

The rotational speeds at which cavitation begins were determined by slowly increasing the speed while listening for "bursts". For water and for 10-wppm polymer this speed was found to be in the range of 1400-1450 rpm and 1450-1500 rpm respectively. For all concentrations greater than 10 wppm, a rotation rate of 1550 rpm was found to be necessary before cavitation began.

For each rotation rate above threshold, the mean and standard deviation (50% of the data lie within the standard deviation) were determined from 10 measured bubble counts. These results are tabulated in Table I and plotted in Figure 12.

These data were used to calculate the percent of cavitation reduction defined by:

$$\frac{\bar{N}_w - \bar{N}_p}{\bar{N}_w}$$

where $\bar{N}_w$ and $\bar{N}_p$ are the mean 10-sec bubble count in water and polymer solution respectively. In Figure 12 the percentage reduction is plotted as a function of propeller rotation speed for each concentration tested.

From these graphs it is seen that the addition of drag-reducing polymers into the flow about the propeller reduces the number of cavitation bursts observed per unit time. This reduction results

in a slight shift of the inception threshold to higher rpm and a substantial reduction in cavitation rate at a fixed rpm. Both effects are markedly dependent on concentration for low concentrations, but above 25 wppm the concentration effect becomes much less marked; changes in threshold being too small to measure and cavitation rate slowly decreasing with increasing concentration.

B. SPECTRAL ANALYSIS

The noise spectra for sample bubble collapses in various concentrations is shown in Figure 13. No specific conclusion can be stated; the only general conclusion that can be made is that the higher frequency components are somewhat attenuated in polymer solutions.

VI. SUMMARY AND CONCLUSIONS

This experiment was conducted to determine the effects of dilute solutions of polyethylene oxide on the inception and formation of cavitation on a model propeller. Parameters studied included:

1. Concentrations of 0, 10, 25, 50, and 100 wppm.
2. Rotation rates from 1,300 to 2,000 rpm.
3. Bubble-collapse spectral analysis from 0.015 to 15 kHz.

The following is a summary of observations and conclusions.

1. The inception of cavitation is delayed in solutions of polyethylene oxide as compared to water.

2. The formation rate of cavitation bubbles is reduced in solutions of polyethylene oxide as compared to water.

3. Polyethylene oxide appears to suppress the high-frequency spectra of the radiated noise from a bubble collapse.

If the results of this experiment can be extended to large propellers, then it appears that in the presence of small concentrations of polyethylene oxide, ships could increase their propeller rotation rate, while producing the same amount of cavitation noise.

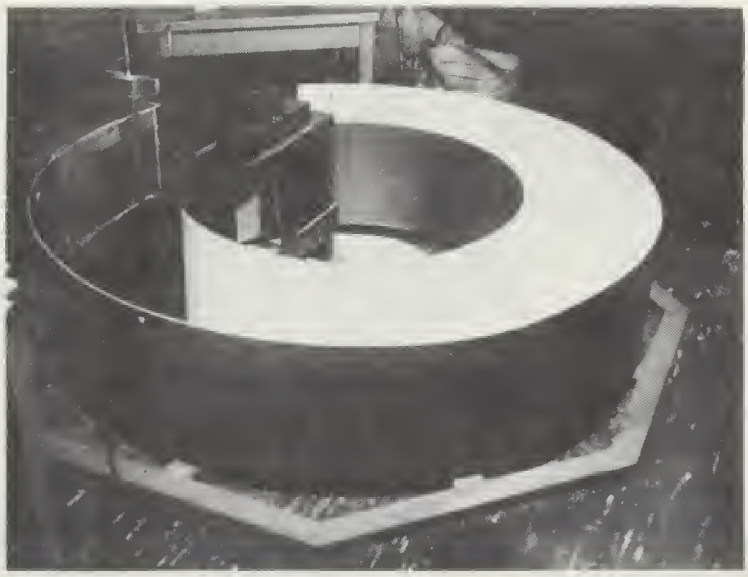

FIGURE 1. ANNULAR STEEL TANK

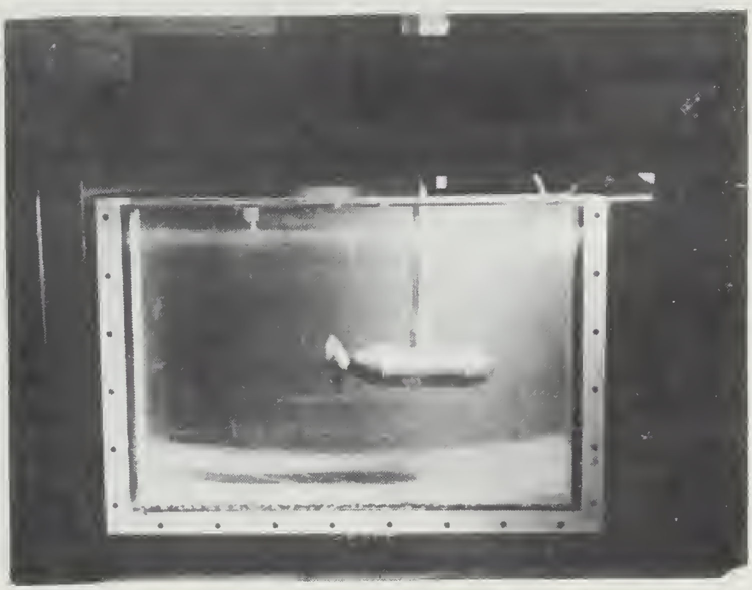

FIGURE 2. PLEXIGLAS VIEWING WINDOW AND MOTOR

FIGURE 3. PLYWOOD COVER

FIGURE 4. WEEDLESS PROPELLER

FIGURE 5. STEEL-BEAM SUPPORT

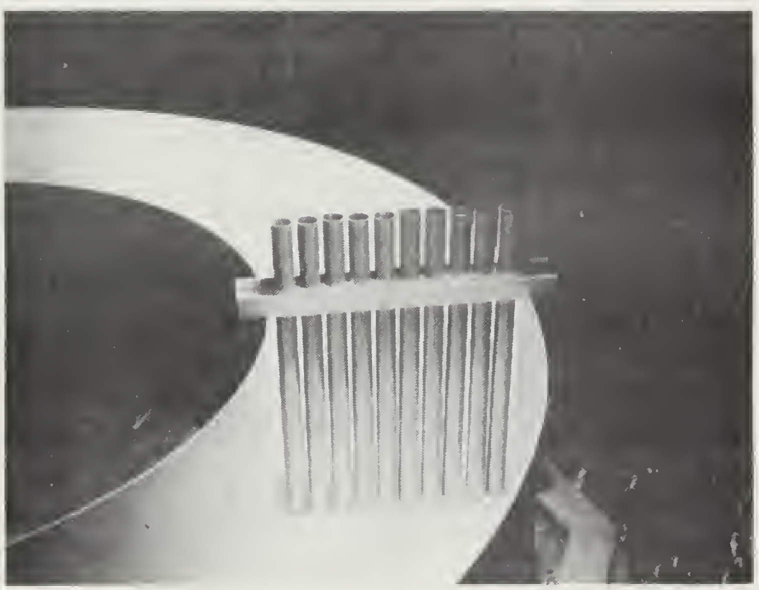

FIGURE 6. FLOW RESTRICTOR

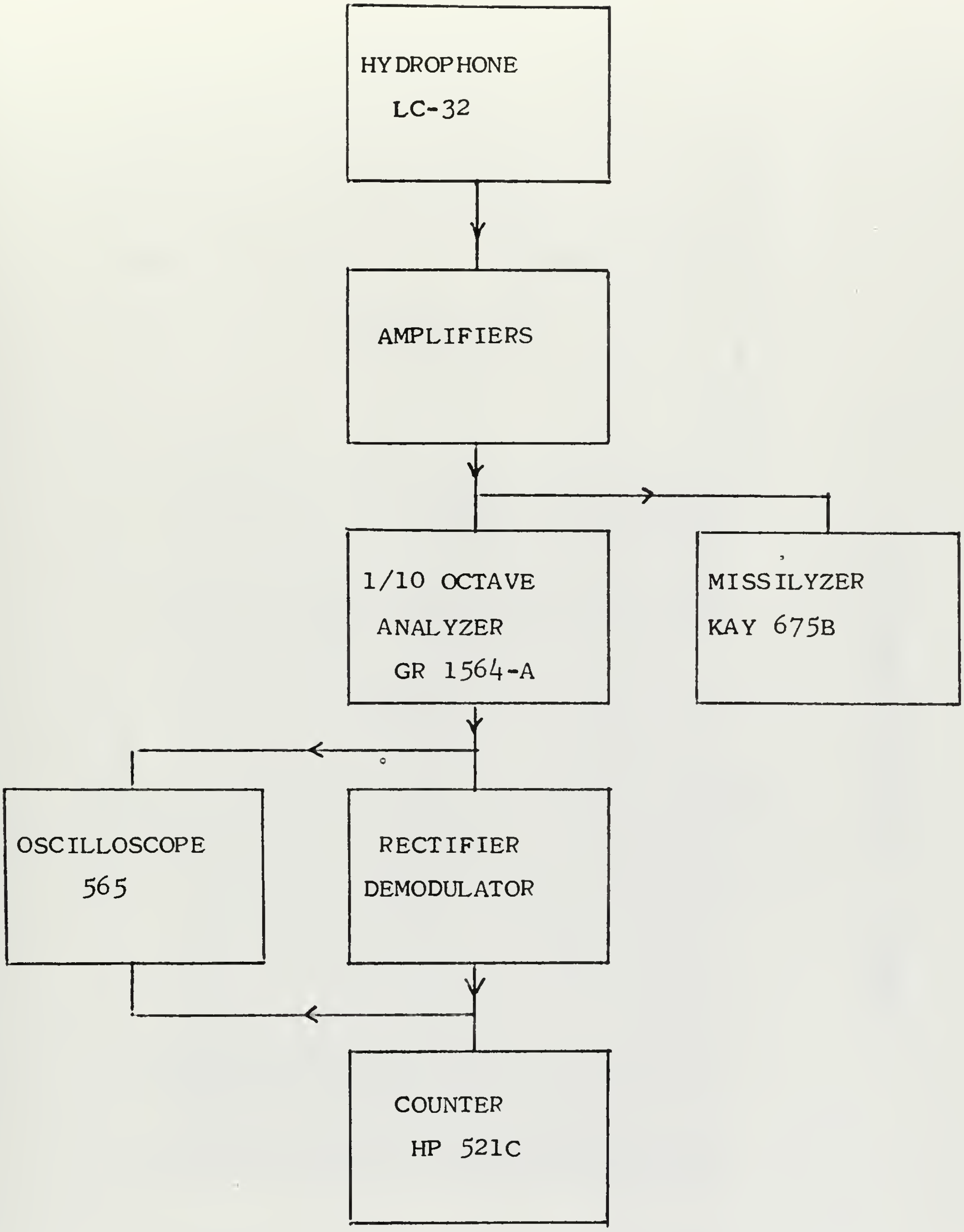

FIGURE 7. RECEIVING AND ANALYZING EQUIPMENT

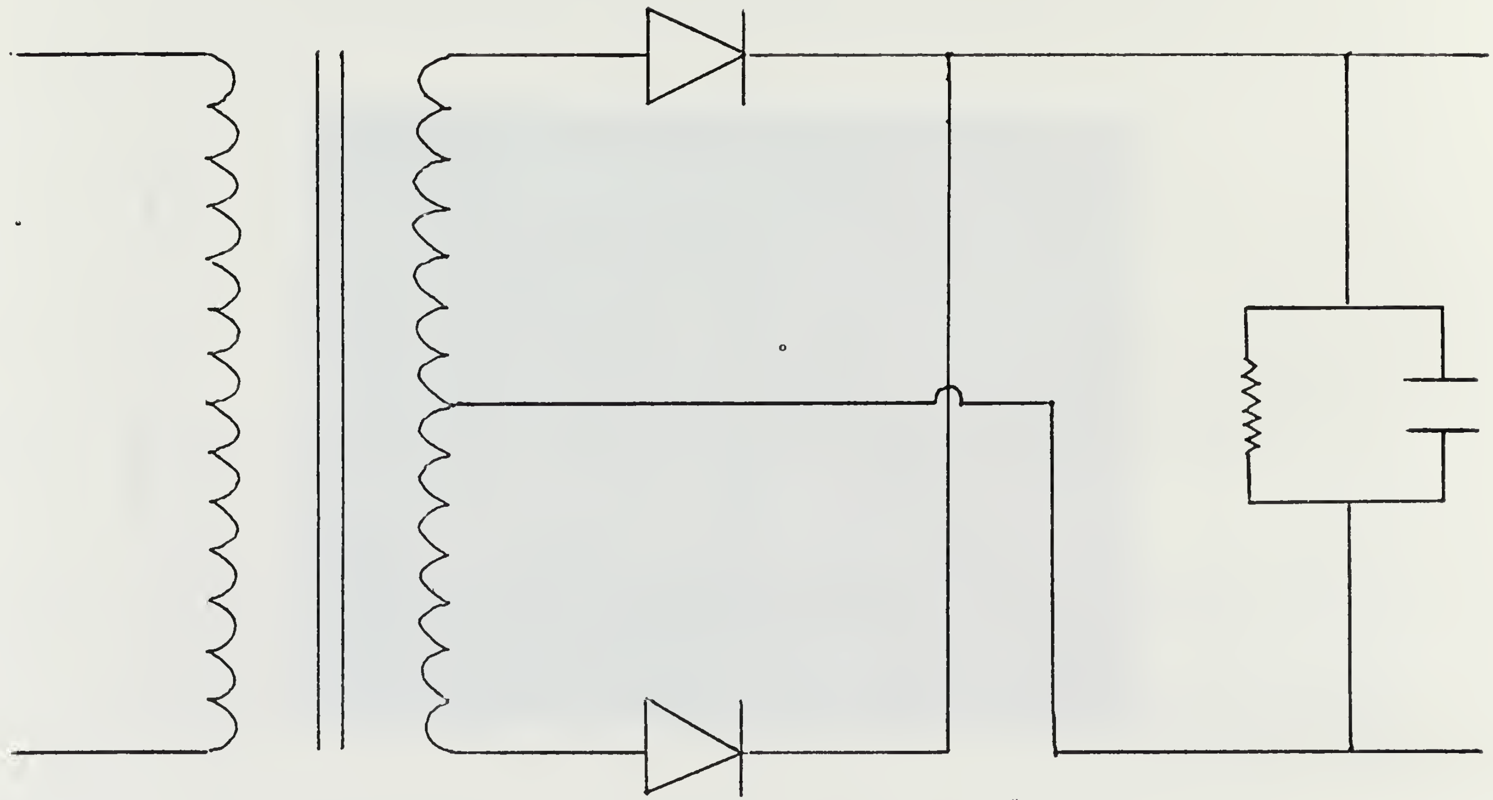

FIGURE 8. RECTIFIER/DEMODULATOR

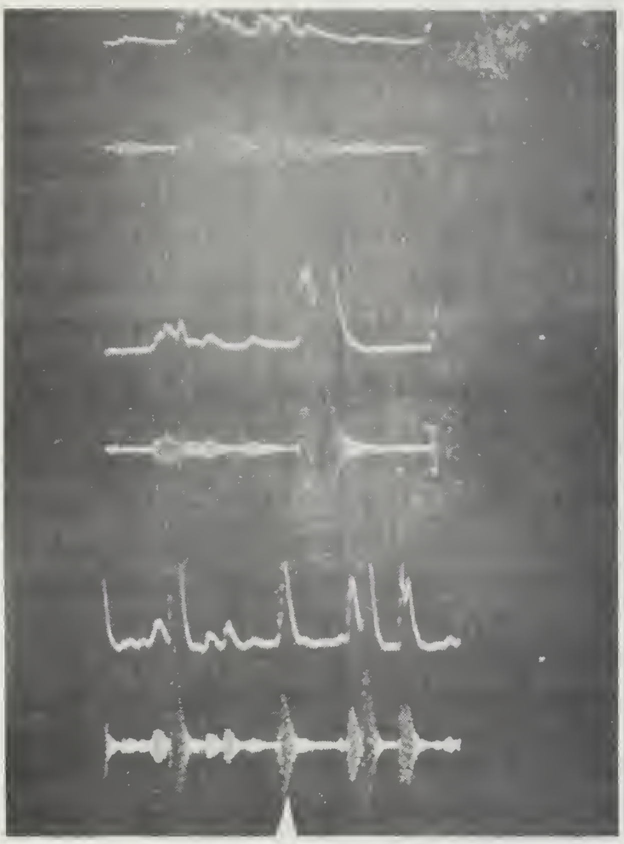

FIGURE 9. WAVE FORMS

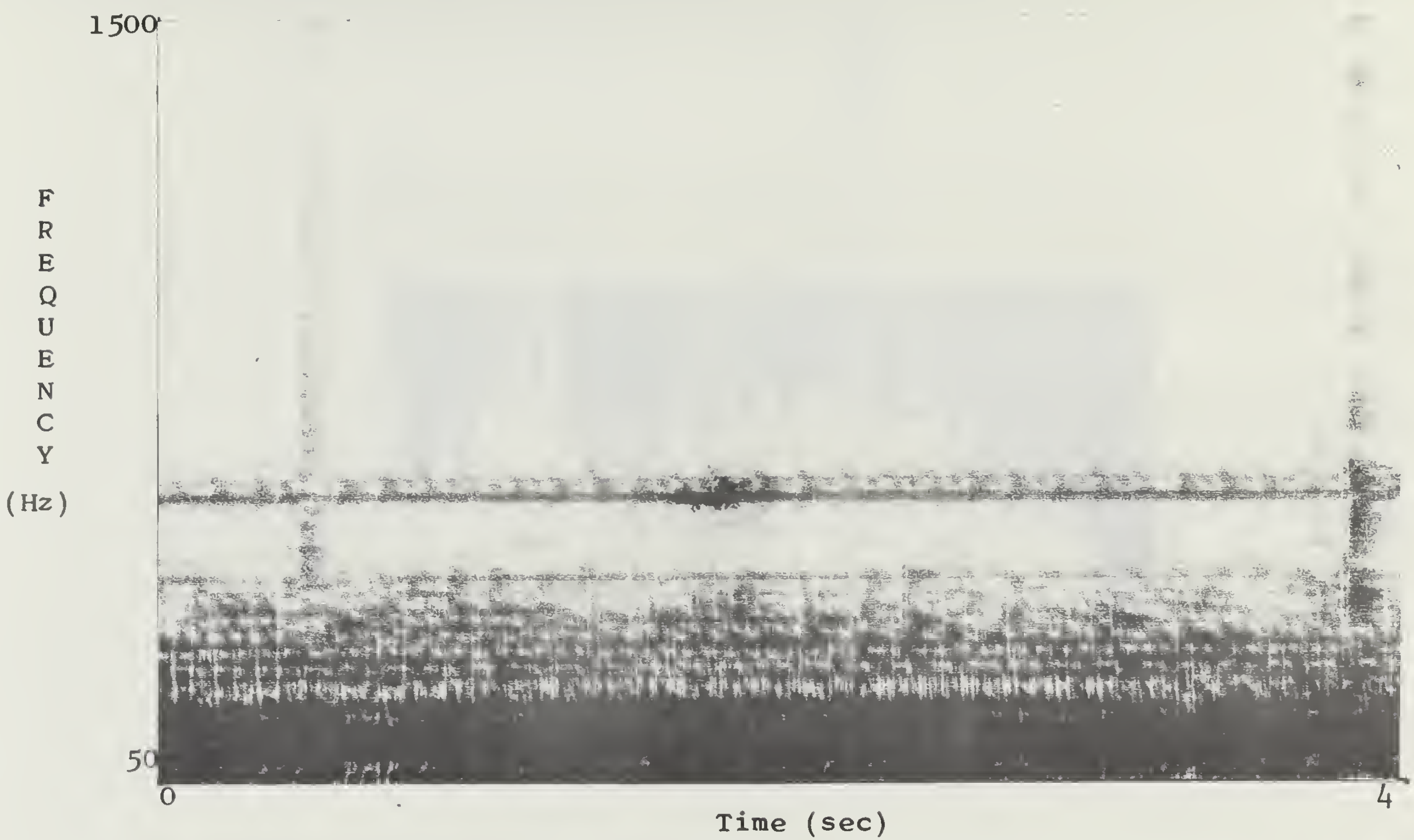

FIGURE 10. UNFILTERED SIGNAL AS A FUNCTION OF FREQUENCY AND TIME

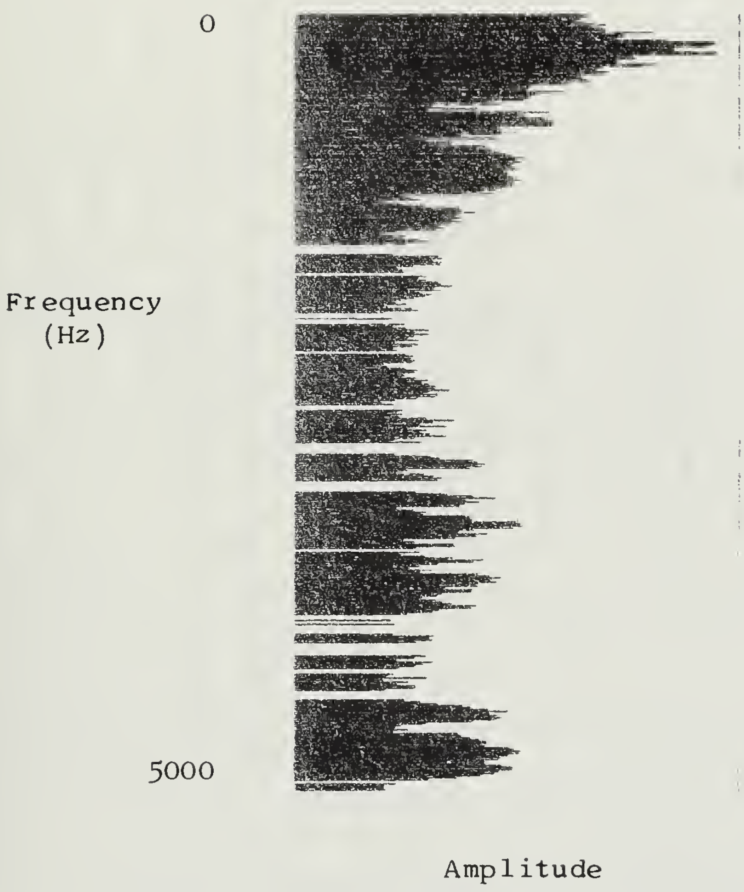

FIGURE 11. FREQUENCY SPECTRUM

WPPM		RPM 1550	1600	1650	1700	1750	1800	1850	1900	1950	2000
0	$\bar{X}$	41.40	95.80	133.30	188.20	261.90	299.40	414.90	388.90	480.10	568.10
	S	10.62	15.85	22.03	29.46	25.02	25.14	32.49	32.39	51.80	23.39
10	$\bar{X}$	21.20	44.10	44.00	91.50	136.89	211.90	253.90	352.10	360.10	491.90
	S	9.04	11.99	9.44	14.86	20.08	39.42	19.55	22.17	19.85	28.02
25	$\bar{X}$	5.30	9.90	18.30	28.90	58.10	89.60	150.90	211.90	284.30	331.40
	S	2.99	3.63	6.62	8.04	8.91	14.20	36.58	36.50	15.44	22.93
50	$\bar{X}$	2.80	9.10	14.10	38.50	48.10	83.80	99.40	109.60	180.90	312.80
	S	1.32	2.18	5.49	15.89	11.89	19.14	10.48	21.54	22.50	35.02
100	$\bar{X}$	3.90	8.50	9.50	19.90	16.50	39.90	59.00	83.10	142.90	233.10
	S	1.90	3.50	3.92	5.90	5.46	10.10	10.51	29.01	40.14	24.10

TABLE I. MEAN AND STANDARD DEVIATION OF CAVITATION BUBBLE COLLAPSES PER 10-SECOND PERIOD FOR VARIOUS CONCENTRATIONS OF POLYETHYLENE OXIDE

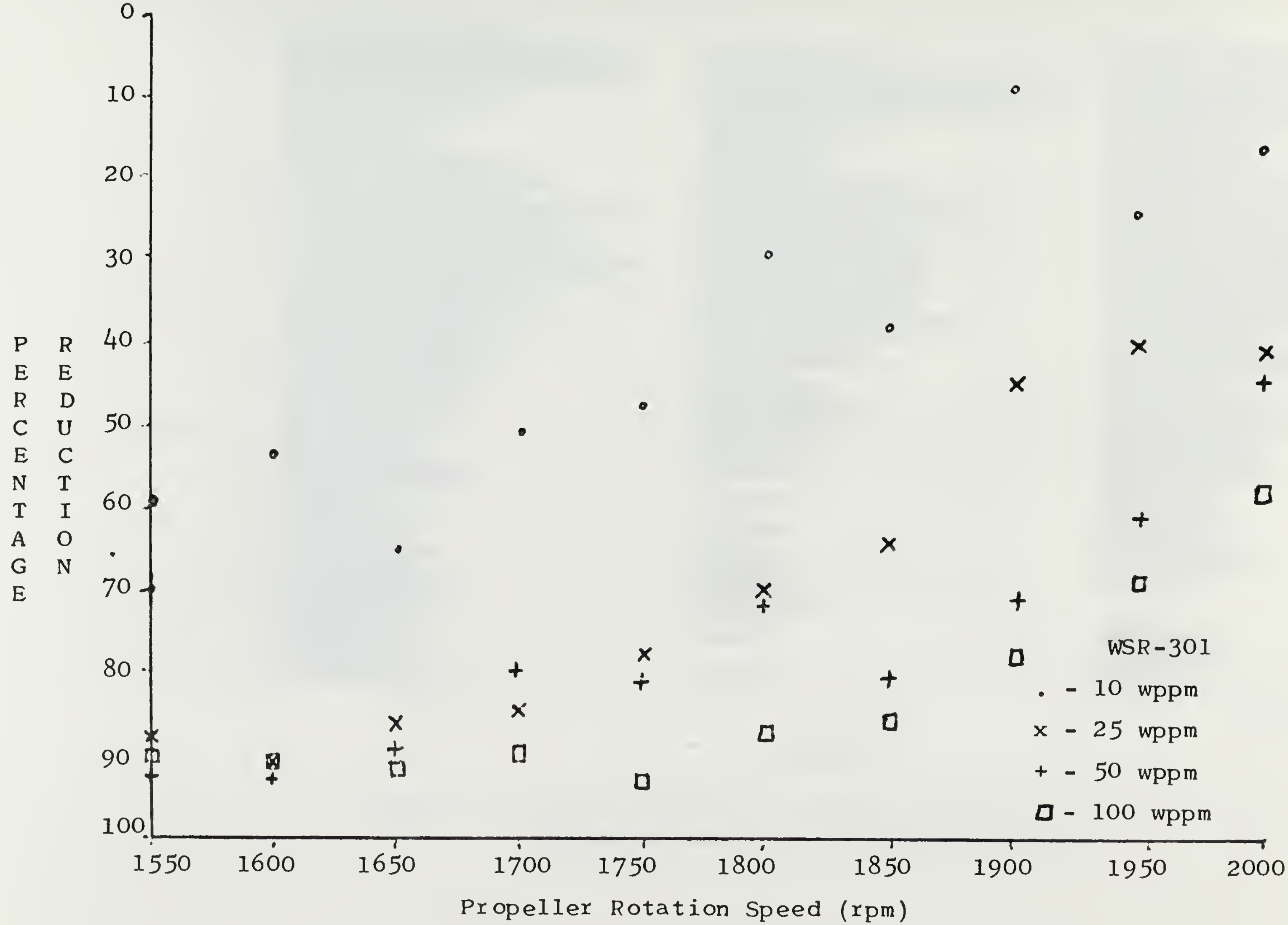

FIGURE 12. PERCENTAGE REDUCTION

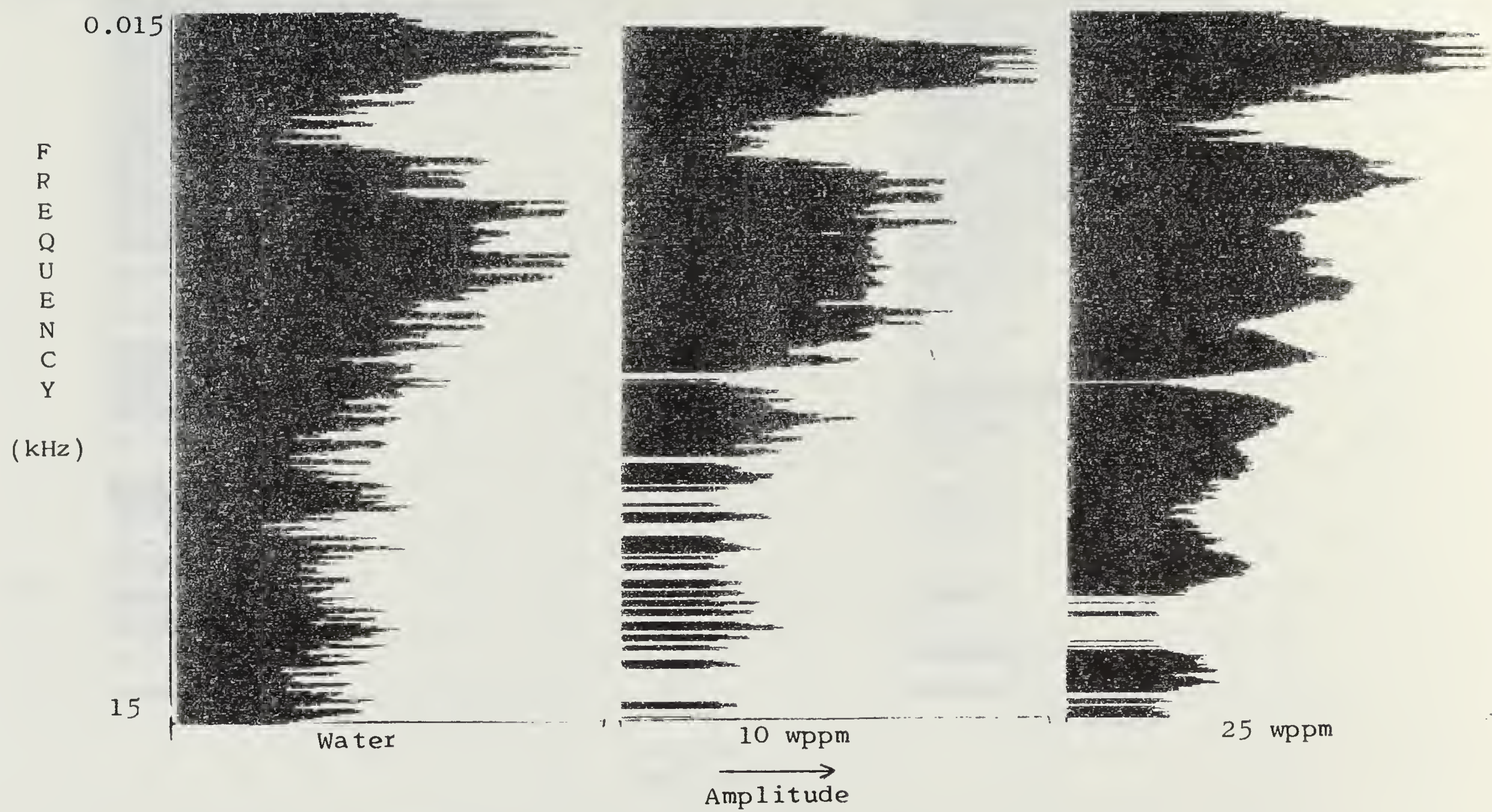

FIGURE 13. NOISE SPECTRUM FOR SAMPLE BUBBLE COLLAPSES IN VARIOUS CONCENTRATIONS OF POLYETHYLENE OXIDE

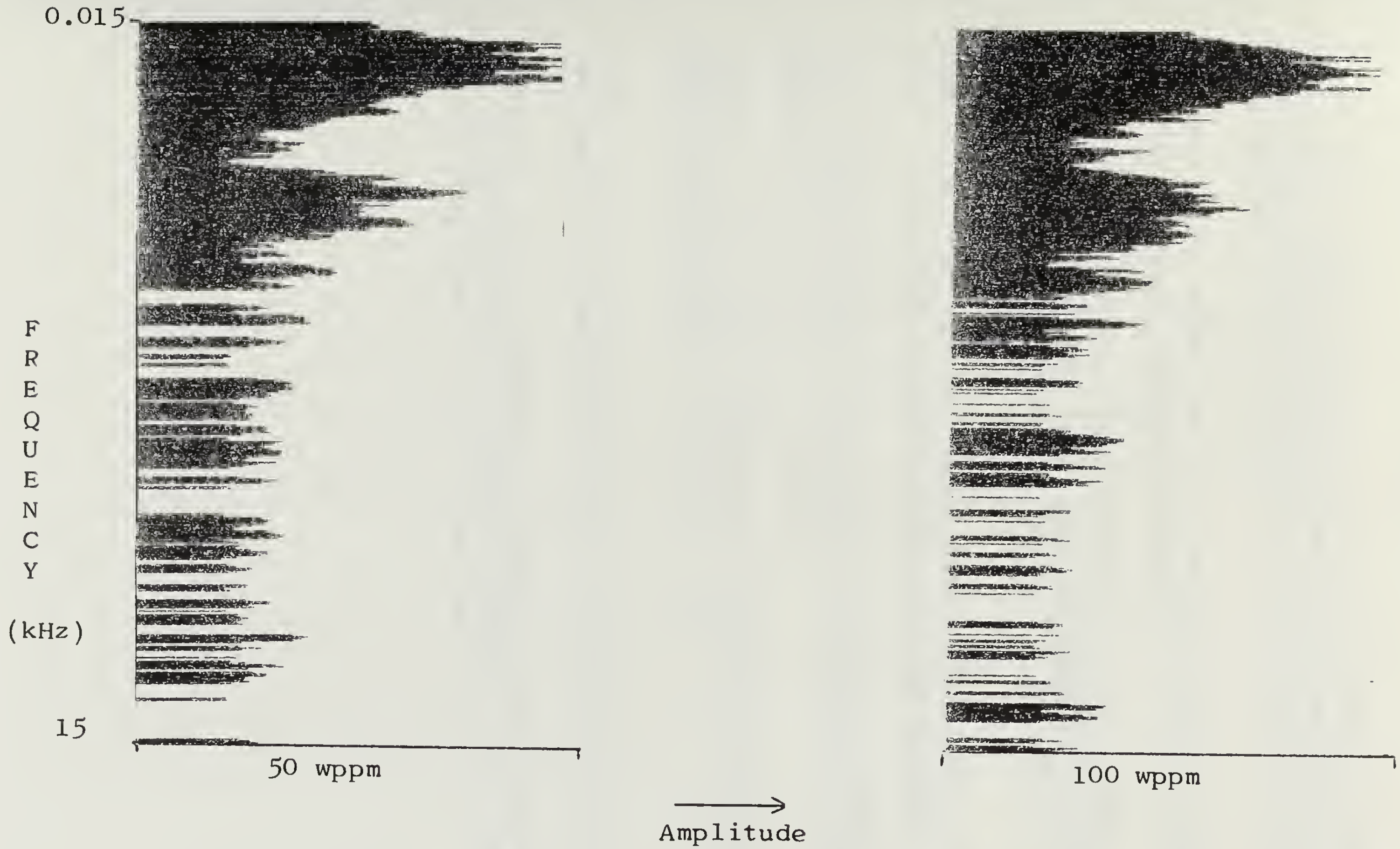

FIGURE 13. CONTINUED

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13. ABSTRACT

The inception and formation rates of bubble cavitation on a 14.8-cm diameter, two-bladed propeller were measured in homogeneous aqueous solutions of polyethylene oxide, WSR-301, at concentrations ranging from 0 to 100 wppm (weight parts per million). Rotational speeds ranged from 1300 to 2000 rpm. At concentrations of 25 wppm and greater, inception was delayed by approximately 150 rpm, and at 2000 rpm the number of bubble collapses measured over a 10-second period was reduced by at least 40 percent. If these results can be extended to full size propellers, ships can increase their propeller rotation rate while producing the same amount of cavitation noise. Measurements of the radiated noise spectra of bubble collapses showed that the higher frequency components are somewhat attenuated in polyethylene-oxide solutions.

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Propeller						
Polyethylene Oxide						
Radiated Noise						
Polymer						
POLYOX						